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Final Technical Report: Airborne Astronomy Program
Grant NAG 2-1074
The Circumstellar Environment of Low Mass Star Forming Regions
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I. Introduction

Since the 1980's, our understanding about the inter-relationship between the collapsing cloud envelope and the disk has been greatly altered. While the dominant star formation models invoke free fall collapse and a $r^{-1.5}$ density profile, other star formation models are possible. These models invoke either different cloud starting conditions or the mediating effects of magnetic fields to alter the cloud geometry during collapse. To test these models, it is necessary to understand the envelope's physical structure. The discovery of disks, based on millimeter observations around young stellar objects, however makes a simple interpretation of the emission complicated. Depending on the wavelength, the disk or the envelope could dominate emission from a star. In addition, the discovery of planets around other stars has made understanding the disks in their own right quite important. Many star formation models predict disks should form naturally as the star is forming. In many cases, the information we derive about disk properties depends implicitly on the assumed envelope properties. How to understand the two components and their interaction with each other is a key problem of current star formation.

To separate out the two components, it is necessary to observe sources at a variety of wavelengths, over a high spatial resolution. As mentioned above, depending on the physical conditions in the disk and the envelope, each will contribute different amounts of flux at each measured wavelength. In addition, high spatial resolution should allow us to resolve the envelope emission. Envelope emission typically extends over many hundreds of AU, whereas the disk will be confined to a much smaller area. By combining high resolution multiwavelength data with radiative transfer models, one can assess the likely contribution of both the disk and the envelope. The envelope contribution dominates the far-infrared emission, with as much as 80% of the total flux coming from the cool dust found in the outer portions of the envelope. This emission can be detected and mapped with high resolution observations, such as the Yerkes Far-InfraRed (FIR) Camera on board the Kuiper Airborne Observatory (KAO). In 1993 and 1995, we obtained far-infrared (60, 100, 160, 200 micron) images for a number of young stellar objects (YSOs) with the KAO prior to the KAO's shutdown.

In the proposal covered by the grant (NAG-2-1074), we proposed to analyze the data, acquire additional data at other wavelengths for models, and to develop source models for the YSOs under study. Based on the results of these models, we hope to define the range of physical conditions that are expected in young stellar systems of different ages and masses. Through the Airborne Astronomy program, we were able to accomplish many of our project goals.

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II. Observational Data Acquired for Source Models

Far-Infrared Images: In FY 93 and FY95, we were awarded two flights each year to study the envelope arounds low mass protostars in Taurus. Working with the Yerkes FIR camera, we obtained data on a total of 13 sources. The Yerkes FIR camera contained an 80 element array. Our standard observing method was to dither the array around the desired source position, and to take a series of images for later coadding. Initial data reduction indicated that most of the sources were compact, as would be expected for low luminosity protostars surrounded by an infalling envelope. Such objects will not tend to heat up a lot of the envelope, and what dust is heated will be concentrated towards the center. However, two sources (L1527 and L1551NE) appeared to show extended emission. This was particularly interesting since these objects may be the the youngest objects in the sample. The claim of youth is based on their spectral energy distributions (SEDs), which are peaked very strongly in the FIR. Such a peak implies that the object is still deeply enshrouded in dust.

Our initial data reduction was based on smoothing the data with a relatively broad smoothing function (i.e. a Gaussian beam). The smoothing resulted in the data being far from the diffraction limit. To address this situation, we undertook (with the Yerkes group) to re-reduce the data using improved convolution methods. Due to the desire, we had to spend considerable time to achieve the diffraction limit. These new results are still being analyzed, however, they confirm the detection of extended emission around L1551NE and L1527. The final models of the KAO results are still in preparation.

To supplement the KAO data, we obtained observations at related wavelengths for a number of the sources in our KAO dataset.

Mid-Infrared spectra: A large sample of T Tauri stars was studied by Cohen and Witteborn in 1985 at 10 μm . To extend this survey, we obtained R=200 spectra for several T Tauri stars, and a more extended sample of Herbig Ae/Be stars. These stars have a variety of 9.8 μm silicate emission. This emission feature reveals that optically thin silicate dust is in the system. Such dust is similar (spectroscopically) to dust seen around some Vega-like objects like Beta Pic.

The passage of comet Hale Bopp provided an opportunity to measure the spectroscopic properties of comets for comparison with our T Tauri and Herbig Ae/Be sample. The comet spectra was found to have some features that were time variable. The comet spectra reveal the presence of grain components that might be pre-solar (based on comparison with IDP spectra). We hope to tie the Comet Hale Bopp work to our FIR/MIR studies in our final models.

Mid-Infrared images: Using the MIRAC2 (Mid-Infrared Array Camera), we imaged several of the embedded YSOs at 10 μm . These observations provide high

sensitivity high spatial observations of the circumstellar environment on size scales of 150 AU. Most of the observations are consistent with the mid-infrared emission as coming from a disk. Extended emission is possible, since we found several examples in related studies of Herbig Ae/Be stars. However, in general, the T Tauri/embedded low mass stars are too cool to heat an extended envelope unless some unusual grain heating mechanism is invoked.

We obtained 10 and 20 μm images of the Trapezium cluster, with its proplyds, which we are currently analyzing to provide a comparison with our isolated stars. Initial results are being published in Deutsch et al (1999).

Submillimeter/millimeter photometry: We focused on Taurus embedded YSOs and the Vega-like stars. In the case of the Taurus sources, which includes our KAO sample, we have obtained a complete survey of the 450-2000 μm emission using the JCMT 15 meter telescope. For the Vega-like stars, we used the CSO 10m and IRAM 30m telescopes to get 800 and 1300 μm photometry. The data will be written up in two papers.

Submillimeter/Millimeter Interferometry:

A number of our sample stars have data already available in the literature. For those sources not already observed, we obtained 1.3 mm interferometry data for the brightest 16 YSOs in our Taurus sample. These observations extended a previous survey we had done. We detected 14/16 sources (Wannier *et al.* 1999 in prep). Of particular interest, we discovered evidence for a couple of binaries in our sample (L1551NE). This dataset is to be combined with published interferometer 2.7 mm data reported in several surveys. We also were awarded time to study a sample of Taurus YSOs with the JCMT-CSO Single-Beam-Interferometer, and got data on DG Tau, among other sources.

Summary: We have obtained the complete SED from 10 microns out to 1.3mm for all of our sources. We have the FIR imaging data, processed to reveal the maximum angular resolution possible, which allows us to model the disk. To model the disk, we have the high resolution millimeter interferometry data.

III. Modeling Techniques Developed for Source Models

At the start of our KAO research, we had one primary modeling technique: a 1-D radiative transfer code that allowed us to explore a variety of density gradients and grain properties. We also developed a way to including disk emission in our model. With these models, we can explore many types of disk/envelope models.

We identified two other radiative transfer codes that would be useful for our models:

1.) Inclusion of Polycyclic Aromatic Hydrocarbons (PAHs) and small grain heating for the models. This code, developed by Siebenmorgen, Krugel, and Mathis (1992), allows us to do spatial models of the PAH emission and small grain emission. Such effects are critical to understanding the emission from a number of the Herbig Ae/Be stars we have under study.

2.) A fast 2-D code: Developed at Jena by Dr. Men'shchikov, it can handle both deeply embedded sources as well as visible disks. It has been applied by Dr. Men'shchikov to L1551 and HL Tau. We intend to apply it to our more deeply embedded sources (L1551NE and L1527).

Overall, there are three important parameters we examine:

1) The envelope geometry and temperature structure.

This is best done with the SED and spatially resolved data at far-infrared/sub-millimeter wavelengths.

2) The disk geometry and temperature structure.

This is most sensitive to the mid-infrared emission, due to the role of small grains or PAHs. High resolution data at 10 microns provides the best constraints.

3) The dust properties in both the envelope and the disk.

The models allow a tradeoff (to a limited extent) between dust properties and the inner structure of the disk/envelope system. However, the presence or absence of silicates is strongly limited by the 10 micron spectra.

IV. Results to date

Combined with our initial KAO program, we find:

1.) The vast majority of embedded YSOs in Taurus are compact at 100 microns. The models most consistent with our data and other observations are either dominated by disk emission (for sources like GG Tau) or envelopes that have relatively steep density gradients ($r^{-1.5 \text{ to } -2.0}$).

2.) The submillimeter/millimeter photometer suggests that envelope models (such as those of Hartmann *et al.* (1993) are very successful. However, in a few cases) they are clearly missing a component in their models. Disk emission plays an important role and must be considered when predicting the overall emission. (Butner *et al.* 1999b(in preparation)).

3) In the two cases where we seem to have extended emission, we have to investigate other possible source models than a Shu collapse. This work is still in progress. We will consider models such as those of Hartmann *et al.* (1995), which invoke a flat sheet rather than spherical collapse.

V. Future Work

We still doing the final modeling for the revised FIR maps, and anticipate having two or three papers done by the end of the year. These papers will present our data and the complete set of parameter space that we explore. In particular, we wish to assess the role of flat sheet collapse models (see point 3 above) in explaining our Taurus FIR data.

VI. Papers in Preparation or Published

The following papers were supported in part by the Airborne Astronomy Grant NAG 2-1074. The support provided salary, travel funds, or equipment used for data reduction and analysis.

Refereed Articles

- H. J. Walker, V. Tsikoudi, C. A. Clayton, T. Geballe, D. H. Wooden, & H. M. Butner, "The Nature of the unusual source IRAS 18530+0817," 1997, *A&A*, 323, 412.
- H. M. Butner, H. J. Walker, D. H. Wooden, & F. C. Witteborn, "1997." Examples of Comet-Like Spectra Among β Pic-Like Stars, in *Astronomical and Biochemical Origins and the Search for Life in the Universe*, ed. C. B. Cosmovici, S. Bowyer, & D. Werthimer (Bologna: Editrice Compositori), p.149.
- G. H. Moriarty-Schieven & H. M. Butner, "A Sub-Millimeter-Wave 'Flare' From GG Tau?," 1997, *Ap. J.*, 474, 768.

Selected Unrefereed Articles

- A. Natta, & H. Butner, "Resolving Disks in YSOs." 1996, in *Infrared Space Interferometry*, ed. A. Alberdi, T. de Graauw, C. Eiroa, C. J. Schalinski, and H. Thronson (Space Science Reviews), in press.

Papers in Preparation

- H. M. Butner, G. H. Moriarty-Schieven, P. Wannier, "Spectral Energy Distributions in Taurus," 1999, *Ap.J.*, in preparation.
- H. M. Butner, G. M. Moriarty-Schieven, *et al.*, "FIR Imaging of Low Mass Sources in Taurus," 1999, *Ap.J.*, in preparation.
- L. K. Deutsch, M. Kassis, N. Smith, J. I. Hora, G. G. Fazio, H. M. Butner, W. F. Hoffman, A. Dayal, "Wide-Field Thermal Imaging of the Orion Nebula at High Spatial Resolution," 1999, *Ap.J.*, in preparation.
- P. G. Wannier, J. Keene, G. Moriarty-Schieven, and H. M. Butner, "1.3 MM interferometry of Taurus Sources," 1999, *Ap. J.*, in preparation.
- D. H. Wooden, H. M. Butner, & F. C. Witteborn, "A Mid-Infrared Survey of T Tauri Stars." 1999, *Ap. J.*, in preparation.

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- Butner, H. M., Walker, H. J., Wooden, D. H., & Witteborn, F. C. 1999a, *Ap. J.*, in preparation.
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- Hartmann, L., Kenyon, S. J., and Calvet, N. 1993, *ApJ*, **407**, 219.
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- Marsh, K. A., and Mahoney, M. J. 1992, *ApJ*, **395**, L115.
- Moriarty-Schieven, G. H. and Butner, H. M. 1997, *Ap. J.*, **474**, 768.
- Wooden, D. H., Butner, H. M., & Witteborn, F. C. 1999, *Ap. J.*, in preparation.
- Wannier, P. G., Keene, J., Moriarty-Schieven, Butner, H. M. 1999, *Ap. J.*, in preparation.